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Superconducting ECR ion source: From 24-28 GHz SECRAL to 45 GHz fourth generation ECR

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The development of superconducting ECR source with higher magnetic fields and higher microwave frequency is the most straight forward path to achieve higher beam intensity and higher charge state performance. SECRAL, a superconducting third generation ECR ion source, is designed for 24-28 GHz microwave frequency operation with an innovative magnet configuration of sextupole coils located outside the three solenoids. SECRAL at 24 GHz has already produced a number of record beam intensities, such as $^{40}Ar^{12+}$ 1.4 emA, $^{129}Xe^{26+}$ 1.1 emA, $^{129}Xe^{30+}$ 0.36 emA, and $^{209}Bi^{31+}$ 0.68 emA. SECRAL-II, an upgraded version of SECRAL, was built successfully in less than 3 years and has recently been commissioned at full power of a 28 GHz gyrotron and three-frequency heating (28 + 45 + 18 GHz). New record beam intensities for highly charged ion production have been achieved, such as 620 eμA $^{40}Ar^{16+}$, 15 eμA $^{40}Ar^{18+}$, 146 eμA $^{86}Kr^{28+}$, 0.5 eμA $^{86}Kr^{33+}$, 53 eμA $^{129}Xe^{38+}$, and 17 eμA $^{129}Xe^{42+}$. Recent beam test results at SECRAL and SECRAL II have demonstrated that the production of more intense highly charged heavy ion beams needs higher microwave power and higher frequency, as the scaling law predicted. A 45 GHz superconducting ECR ion source FECR (a first fourth generation ECR ion source) is being built at IMP. FECR will be the world's first Nb_3Sn superconducting-magnet-based ECR ion source with 6.5 T axial mirror field, 3.5 T sextupole field on the plasma chamber inner wall, and 20 kW at a 45 GHz microwave coupling system. This paper will focus on SECRAL performance studies at 24-28 GHz and technical design of 45 GHz FECR, which demonstrates a technical path for highly charged ion beam production from 24 to 28 GHz SECRAL to 45 GHz FECR. *Published by AIP Publishing.* https://doi.org/10.1063/1.5017479

I. INTRODUCTION

High power heavy ion accelerator has opened many new research opportunities for nuclear physics, atomic physics, and other disciplines as well. Because highly charged ion beams enable the accelerators to produce very energetic ions at substantially lower cost and much smaller machine footprints, increasing demands for more intense and higher charge state heavy ion beams by the high power heavy ion accelerator have dramatically promoted the development of highly charged ion source technology and ion source physics study. Many of the under-construction and next generation heavy ion accelerators require very intense highly charged heavy ion beams, for example, 15 emA of pulsed $^{238}U^{28+}$ beam for FAIR,[1] 13 pμA of CW (continuous wave) $^{238}U^{34+}/U^{33+}$ for FRIB,[2] and 1 emA of CW $^{36}Ar^{12+}$ for SPIRAL2.[3] HIAF,[4] a next generation High Intensity heavy ion Accelerator Facility (HIAF) to be built by IMP, requires the ion source to be able to deliver 50 pμA of pulsed $^{238}U^{35+}$ and 30 pμA of CW $^{238}U^{35+}$ beams, even higher charge state such as $^{238}U^{45+}$, in order to get a higher energy gain and make the accelerator more compact with lower cost. However, these beam intensities with a good long-term stability required by those accelerator facilities have not yet been achieved by any existing ion sources.

The ECR ion source is an only highly charged heavy ion source being able to produce both CW and pulsed ion beams.[5] Recent developments of superconducting ECR ion sources operating at 24-28 GHz, such as LNS-SERSE,[6] LBNL-VENUS,[7,8] IMP-SECRAL,[9–11] RIKEN-SC-ECRIS,[12] MSU-SuSi,[13] and so on, have demonstrated that the ECR ion source operating at higher magnetic fields and higher heating microwave frequency is the most straight-forward path to achieve higher source performance. Nevertheless, technical challenges have been encountered during these developments, such as the difficulties in fabricating a higher-field superconducting magnet, the high power microwave coupling, strong bremsstrahlung radiations, the intense multiply charged ion beam extraction and transport, and the long-term beam stability at high intensity and high operation power as well.[11] Based on the demonstrated performance of those superconducting ECR ion sources operating at 24-28 GHz, a 4th generation ECR ion source operating at higher magnetic fields and higher heating microwave frequency 40-60 GHz will certainly produce higher beam intensities with higher charge state and will be able to meet all of the aforementioned demands.

Intensive research studies and developments on the high performance superconducting ECR ion source at 24-28 GHz have been conducted at IMP in order to meet requirements of the existing accelerator facility HIRFL and the future facility HIAF. SECRAL, a superconducting third generation ECR ion source for 24-28 GHz microwave frequency operation with an innovative magnet configuration,[11] has been operated to provide highly charged heavy ion beams for an HIRFL accelerator since 2007.[14] SECRAL-II,[15] an upgraded version of SECRAL, was built successfully in less than 3 years and has recently been commissioned at full power of a 28 GHz gyrotron. FECR, the world's first fourth generation ECR ion source with a Nb_3Sn superconducting-magnet and operating at the 45 GHz/20 kW microwave coupling system, is being developed at IMP.

II. SECRAL and SECRAL-II PERFORMANCE AND DEVELOPMENT AT 24-28 GHz

A. SECRAL and SECRAL-II status

SECRAL is a third generation ECR ion source with the magnetic field maxima of 3.6 T on the axis and 2.0 T radially at the plasma chamber inner wall, for operations with heating microwave up to 24-28 GHz.[9–11] The minimum-B magnetic field configuration of SECRAL source is produced by an innovative superconducting magnet structure of sextupole coils located outside the three solenoids, which is reversed to the conventional structure of the superconducting ECR ion source. Figure 1 schematically shows the key footprints of SECRAL, ion beam analysis and beam intensity measuring device, and vacuum pumps. The goal of SECRAL is to enhance the production of highly charged heavy ion beams with reliable long-term stability needed for the HIRFL heavy ion accelerator.

The first beam from SECRAL was available in 2005,[16] and SECRAL has been delivering highly charged heavy ion beams to the HIRFL accelerator since 2007.[14] Depending upon the required ion beam and intensity, SECRAL can flexibly operate at 18 GHz only or 24 + 18 GHz to provide particularly those heavy ion beams with a high charge state unavailable with the room temperature ECR source LECR3 in terms of beam intensity, such as Ar^{15+}, Ni^{19+}, Kr^{19+}, Sn^{26+}, Xe^{27+}, Bi^{36+}, and U^{32+}. Figure 2 shows the beam delivery time by SECRAL from May 2007 to December 2016, accounting for more than 3000 annual hours in 2012-2016. The total beam delivery time from the SECRAL to HIRFL accelerator so far is more than 28 000 h by June 2017.

Besides beam operation for an HIRFL accelerator, SECRAL has been dedicated to high intensity beam studies for highly charged heavy ions and also ion source performance

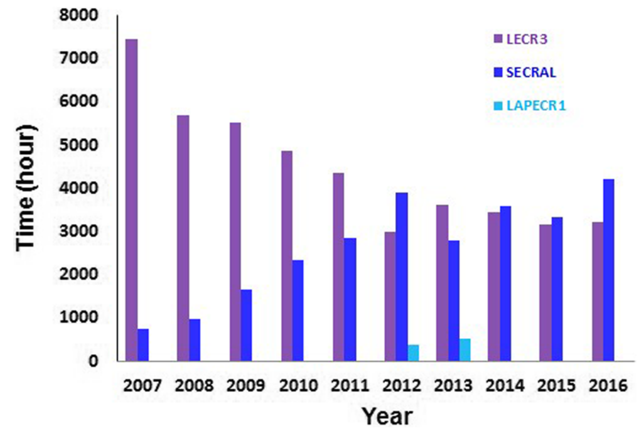

FIG. 2. Beam delivering time by SECRAL from May 2007 to December 2016 in comparison to LECR3.

studies including high power microwave coupling, magnetic field effect, multi-frequency heating, beam quality, and long-term stability. Beam intensities produced by SECRAL have been increased by a factor of 3-10 in the past years due to intensive development and beam tests. The detailed results were published recently in Ref. 11.

A new superconducting ECR ion source, SECRAL-II, has been built successfully within 3 years for an HIRFL cyclotron injector.[15] SECRAL-II is almost a duplicate of SECRAL except the cryogenic system and a slightly higher radial field with a larger plasma chamber for operation at 28 GHz. The cryogenic system of SECRAL-II was designed to be operated with 5 GM coolers that are capable of providing a dynamic cooling capacity of more than 5 W to the 4.2 K reservoir to mitigate the dynamic heat load due to the strong bremsstrahlung radiation. Figure 3 shows the SECRAL-II ECR source which is under beam commissioning and studies on the production of high intensity highly charged ion beams.[17] SECRAL-II has been commissioned at 8-10 kW microwave power with 18 GHz + 28 GHz double-frequency heating, and a number of record beam intensities were produced. Recently SECRAL-II is being tested with the 45 GHz microwave gyrotron system to study 45 GHz high

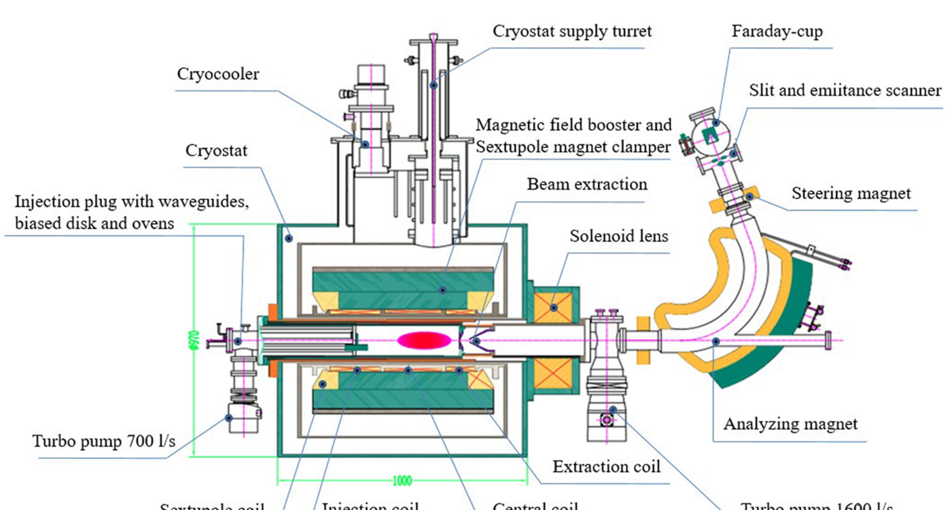

FIG. 1. Layout of the SECRAL ion source and its beam transport line.

FIG. 3. SECRAL-II ECR ion source at beam commissioning.

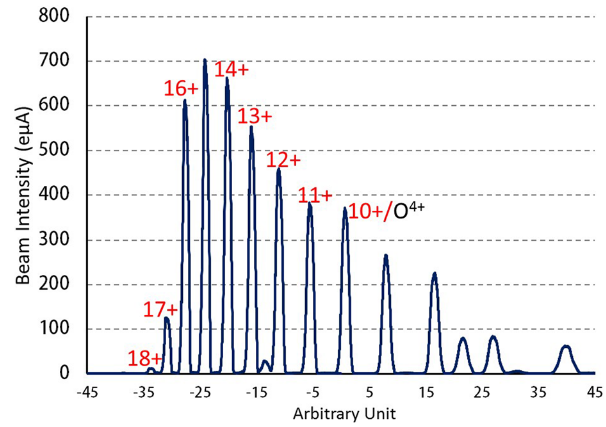

FIG. 4. Argon beam CSD spectrum with the SECRAL-II source optimizing for $^{40}Ar^{16+}$. 610 eμA of $^{40}Ar^{16+}$ was produced by double-frequency heating (8.0 kW 28 GHz + 1.4 kW 18 GHz).

power coupling and three-frequency heating with 28 + 45 + 18 GHz. Meanwhile, high intensity beam productions, new microwave coupling, and bremsstrahlung measurements are being conducted with SECRAL-II in order to study ECR source physics and performance.

B. High intensity and high charge state ion beam production

Table I lists the recent SECRAL and SECRAL-II performance of highly charged ion beams produced in 2016-2017 at the extraction voltages of 20-27 kV and the total microwave power up to 6-9 kW, which have created a number of new recorded beam intensities. Figure 4 shows the argon beam charge state distribution (CSD) spectrum produced by the SECRAL-II source optimizing for $^{40}Ar^{16+}$ at double-frequency heating with 8 kW of 28 GHz and 1.4 kW of 18 GHz microwave power and 25 kV extraction voltage. Figure 5 shows the xenon beam CSD spectrum produced by the SECRAL-II source optimizing for $^{129}Xe^{38+}$ at three-frequency heating with 5 kW of 28 GHz, 1.0 kW of 45 GHz, and 0.85 kW of 18 GHz microwave power and 20 kV extraction voltage. It is worth pointing out that, for the first time, pretty high charge state heavy ion beams produced by an ion source, such as $^{40}Ar^{12+}$, $^{40}Ar^{14+}$, $^{86}Kr^{18+}$, and $^{129}Xe^{26+}$, have exceeded the 1.0 emA level in which the ECR ion source community had been working for many years. This may open up some new research opportunities for a nuclear physics and atomic physics based high intensity heavy ion accelerator. It is also the first time for the ECR ion source community to test three-frequency heating with 28 GHz as main frequency and 45 GHz plus 18 GHz as auxiliary frequency. Some nice results for very high charge state xenon beams were produced with the three-frequency heating, such as 53 eμA of $^{129}Xe^{38+}$, 17 eμA of $^{129}Xe^{42+}$, and 1.3 eμA of $^{129}Xe^{45+}$. The experiment with the three-frequency ECR heating for highly charged ion beam production will be conducted again and new results will be reported

The present performance of SECRAL on the production of highly charged ion beams has been enhanced dramatically

TABLE I. Latest beam intensities produced by SECRAL and SECRAL-II.

Ion beam	I (eμA)	Source
$^{16}O^{6+}$	6700	SECRAL-II
$^{40}Ar^{12+}$	1420	SECRAL
$^{40}Ar^{14+}$	1040	SECRAL-II
$^{40}Ar^{16+}$	620	SECRAL-II
$^{40}Ar^{18+}$	15	SECRAL-II
$^{40}Ca^{11+}$	710	SECRAL
$^{40}Ca^{14+}$	270	SECRAL
$^{86}Kr^{18+}$	1020	SECRAL-II
$^{86}Kr^{28+}$	146	SECRAL-II
$^{129}Xe^{26+}$	1100	SECRAL
$^{129}Xe^{27+}$	920	SECRAL
$^{129}Xe^{30+}$	365	SECRAL-II
$^{129}Xe^{34+}$	120	SECRAL
$^{129}Xe^{38+}$	53	SECRAL-II
$^{129}Xe^{42+}$	17	SECRAL-II
$^{209}Bi^{31+}$	680	SECRAL
$^{209}Bi^{41+}$	100	SECRAL
$^{209}Bi^{50+}$	10	SECRAL
$^{209}Bi^{55+}$	1.5	SECRAL
$^{238}U^{33+}$	202	SECRAL

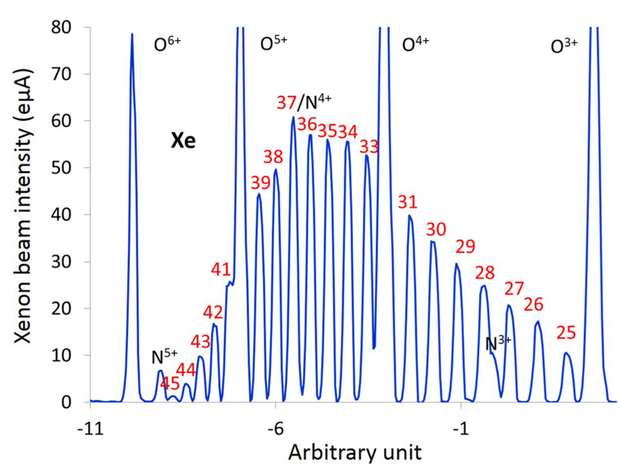

FIG. 5. Xenon beam CSD spectrum with the SECRAL-II source optimizing for $^{129}Xe^{38+}$. 53 eμA of $^{129}Xe^{38+}$ was produced by three-frequency heating (5.0 kW 28 GHz + 1.0 kW 45 GHz + 0.85 kW 18 GHz).

compared to those before 2011. Figure 6 illustrates the SECRAL intensity comparison of highly charged xenon beams between 2011 and 2016. Such enhancement is an accumulation of continuous exploration and component modifications, such as high power operation at double-frequency heating (24 GHz + 18 GHz), new microwave coupling, optimization of the magnetic field distribution, and effective cooling of the key components in the plasma chamber. Particularly, the new microwave coupling scheme with a smaller optimum-diameter of the oversized waveguide has played a key role,[10,18] which not only has contributed 20%-50% beam intensity enhancement but also has enabled SECRAL to operate stably at total microwave power up to 8-9 kW of 24 + 18 GHz. Stable plasma is the first condition for operation of high microwave power and high beam intensity. Stable plasma is determined by component cooling, magnetic field distribution, microwave coupling, material of plasma chamber, source conditioning at high power, and so on.

SECRAL-II was successfully built and commissioned at high microwave power by learning lessons from SECRAL. Table I indicates that some of the results in terms of beam intensities and charge states achieved by SECRAL-II are better than those of SECRAL because of the better vacuum condition, higher microwave frequency heating (28 GHz), higher radial sextupole field on the chamber wall (Ø125 mm), and higher transmission efficiency of the beam line. Performance studies and optimum tuning of SECRAL and SECRAL-II have demonstrated that the source potential has not yet been fully realized, and further explorations should be conducted toward higher charge states and higher beam intensities.

C. Performance study at high microwave power and double-frequency heating

We keep studying the performance of SECRAL and SECRAL-II at high microwave power in the past two years. It turned out that the ion source performance on the production of the highly charged ion beams has been substantially improved by high power operation at double-frequency heating (18 GHz + 24 GHz, 18 GHz + 28 GHz) as the scaling law predicted.[19,20] Figure 7 shows the dependence of $^{129}Xe^{30+}$ beam intensity on the total microwave power achieved at SECRAL with double-frequency heating (24 GHz + 18 GHz), and Fig. 8

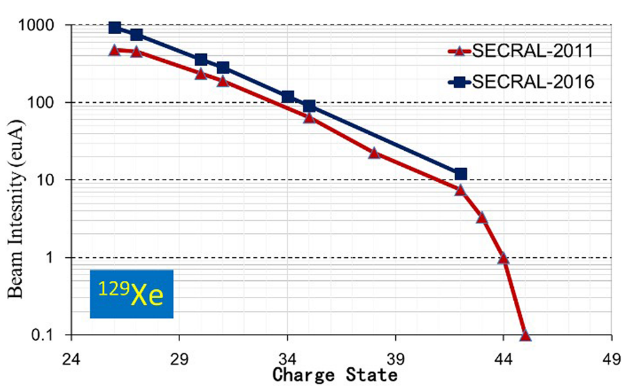

FIG. 6. SECRAL xenon beam intensity comparison between 2011 and 2016.

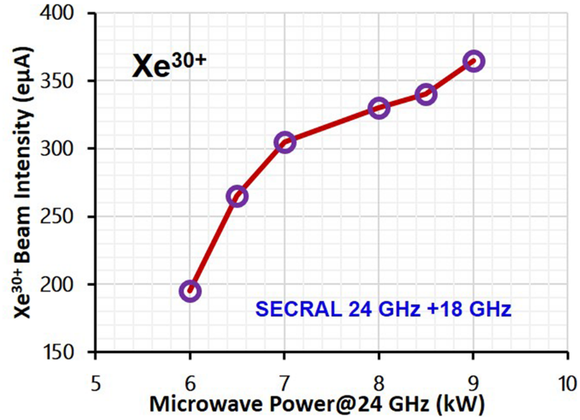

FIG. 7. Dependence of $^{129}Xe^{30+}$ beam intensity on the total microwave power achieved at SECRAL with double-frequency heating (24 GHz + 18 GHz). The 18 GHz auxiliary microwave power level is roughly 1.0-1.5 kW.

shows the dependence of $^{86}Kr^{25+}$ beam intensity on the total microwave power achieved with SECRAL-II using double-frequency heating (28 GHz + 18 GHz). The 18 GHz auxiliary microwave power level is roughly 1.0-1.5 kW in Figs. 7 and 8. Figures 7 and 8 illustrate that beam intensities keep increasing with microwave power and are not saturated even at a total microwave power of more than 9 kW, which implies that higher microwave power is necessary to achieve higher beam intensities. SECRAL and SECRAL-II are always operated at double-frequency heating. The beam test results indicate that the auxiliary microwave power is not only for stabilizing the plasma but also very essential for increasing beam intensities at high power operation. It seems that higher auxiliary microwave power is needed for intense highly charged ion beam production when the main microwave power is higher, as shown in Fig. 9. A typical magnetic field distribution for achieving the results shown in Fig. 9 is B_{rad} = 1.61 T, B_{inj} = 3.40 T, B_{min} = 0.58 T, and B_{ext} = 1.68 T, where B_{rad} is the sextupole radial field on the chamber wall, B_{inj} is the peak value of the mirror magnetic field on the axis at the injection side, B_{min} is the minimum value of the mirror magnetic field on the axis,

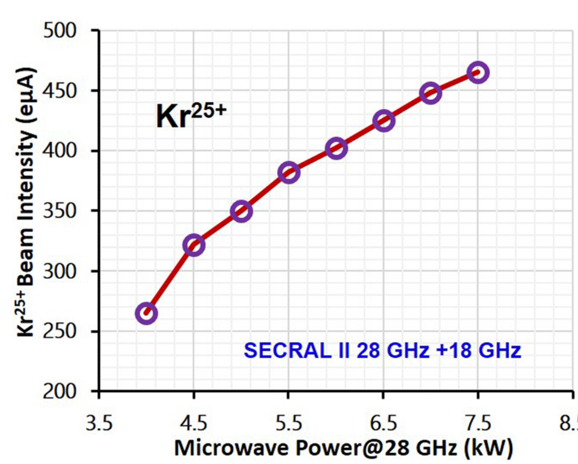

FIG. 8. Dependence of $^{86}Kr^{25+}$ beam intensity on the total microwave power achieved at SECRAL-II with double-frequency heating (28 GHz + 18 GHz). The 18 GHz auxiliary microwave power level is roughly 1.0-1.5 kW.

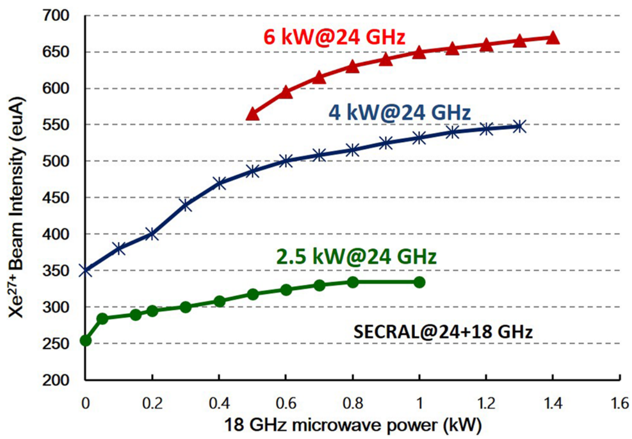

FIG. 9. Effect of the auxiliary microwave power to $^{129}Xe^{27+}$ beam intensity achieved at SECRAL with double-frequency heating.

B_{ext} is the peak value of the mirror magnetic field on the axis at the extraction side.

The frequency effect is significant particularly for very high charge state beam production. The superconducting magnet for SECRAL and SECRAL-II is identical. The key difference for the two sources is that SECRAL is typically operated at 24 GHz and SECRAL II at 28 GHz. Figure 10 shows the argon beam intensities of different charge states at different operation microwave frequencies which demonstrates that higher frequency is obviously favorable for more intense beam production of highly charged ions.

As the scaling laws predicted,[19,20] performance studies with SECRAL and SECRAL-II at high microwave power of frequency 24-28 GHz demonstrate that, for the production of higher intensity of very high charge state beams such as $^{129}Xe^{38\text{-}45+}$ and $^{238}U^{41\text{-}50+}$, we need a 4th generation ECR ion source with microwave frequency more than 40 GHz and power at a level of 20 kW.

III. WORLD'S FIRST FOURTH GENERATION ECR ION SOURCE FECR OPERATING AT 45 GHz

A. 45 GHz FECR overview

To meet the increasing demands for higher beam intensities and higher charge states of heavy ion beams, the concept of the 4th generation ECR ion sources operating at 40-60 GHz microwave frequency has been proposed for almost 10 years and are just under design to reach up to 8.0 T of the injection mirror peak field on the axis and 4.0 T at the plasma chamber wall by using the higher critical-current Nb_3Sn magnets.[21–23] However, there has been no any Nb_3Sn-magnet-based high field ECR ion source or its prototyping magnet being really built. FECR, the world's first fourth generation ECR ion source, is designed to operate at 45 GHz instead of 56 GHz microwave frequency just for minimizing the technical risk and challenge in order to reach reliable and stable long-term operation of the Nb_3Sn magnet needed for the HIAF heavy ion accelerator.

Figure 11 schematically shows the design of the FECR Nb_3Sn superconducting ECR ion source, and Fig. 12 shows how FECR source will look like. The FECR Nb_3Sn magnet consists of four solenoid coils and one sextupole. The designed axial injection peak field is 6.5 T on the axis, the sextupole field at the plasma chamber wall of radius 75 mm is 3.8 T, and the extraction peak field is 3.5 T. The minimum-B field is designed with a dynamical range which could easily be varied from 0.5 up to 1.0 T. The Nb_3Sn magnet assembly is immersed and cooled in a liquid helium bath in the cryostat which is cooled down by 6 sets of GM cryo-coolers with cooling power each one 2.2 W at 4.2 K. The key parameters of the FECR ion source is listed in Table II. FECR will be operated at double-frequency heating at 45 GHz plus 35 GHz microwaves, in which the auxiliary microwave frequency was preliminarily decided as 35 GHz in terms of SECRAL high power operation with 24 GHz plus 18 GHz double-frequency heating. The main heating microwave with frequency 45 GHz and maximum power 20 kW is launched into the plasma chamber through the quasi-optical mirror transmission line and corrugated waveguide.[24] The quasi-optical transmission has to be utilized because FECR is located at a 100-300 kV high voltage platform. The 45 GHz/20 kW gyrotron system from a Russian company GyCOM is ready and being tested with SECRAL-II which already produced the first 45 GHz ECR plasma at 5 kW demonstrating a good microwave coupling.[24] The injection tank integrates together the microwave coupling components, ovens for introducing solid materials, biased disk, gas injection, and vacuum pumping port. The double-wall plasma chamber is made of aluminum with a water cooling channel in between. A 2 mm thick tantalum liner encloses the plasma chamber to mitigate the strong bremsstrahlung thermal load to the magnet cryostat. A 1000 l/s turbo molecular pump and a 2500 l/s turbo molecular pump are installed, respectively, at the injection and the extraction region to achieve a high vacuum needed for the production of highly charged ions. Ions are extracted at a maximum voltage of 50 kV to minimize high intensity beam transport losses, which results in a technical solution that the FECR whole magnet system together with the injection tank and the microwave launching waveguide (as shown in Figs. 11 and 12) is floated at 50 kV high voltage. FECR is expected to produce quite high beam intensity for highly charged heavy ions, such as 1.0 emA of $^{129}Xe^{30+}$, $^{209}Bi^{31+}$, and $^{238}U^{35+}$ and 50 eμA of $^{129}Xe^{45+}$, $^{209}Bi^{55+}$, and $^{238}U^{56+}$.

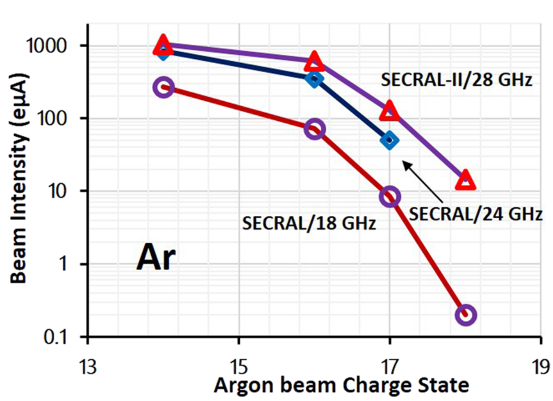

FIG. 10. Argon beam intensities of different charge states at different operation microwave frequencies for SECRAL and SECRAL-II.

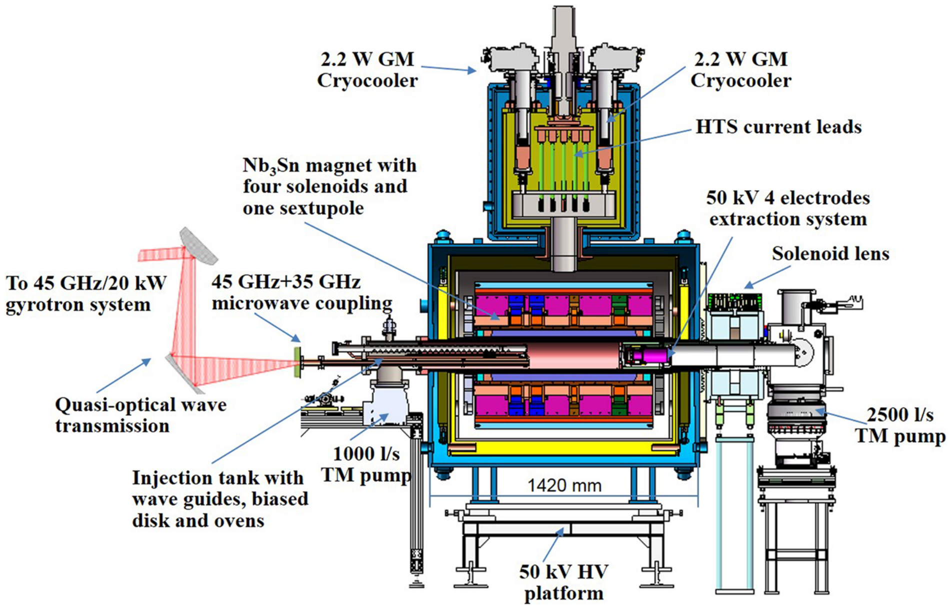

FIG. 11. Layout of 45 GHz FECR.

It is quite challenging to develop the 4th generation high field Nb_3Sn-magnet-based FECR ion source. The main technical challenges are as follows: (1) The biggest technical challenge is the development of the Nb_3Sn magnet composed of four solenoids and one sextupole magnet with the 11.8 T maximum magnetic field on the Nb_3Sn conductor and roughly 150 MPa stress at full current excitation. Winding of the sextupole coils, effective quench protection, and long-term reliability of the magnet are the key issues. (2) 20 kW high power of 45 GHz microwave transmission and efficiently coupling into the ECR plasma. (3) High flux x-ray heating to the magnet cryogenic system due to the strong bremsstrahlung. (4) The 50 kV high voltage beam extraction system with the total mixed beam intensity of more than 20 mA. (5) The production of the high-intensity highly charged uranium beam due to difficulties to produce high enough uranium vapor. (6) The long-term stability and reliability of mA highly charged ion beam operation with low beam emittance.

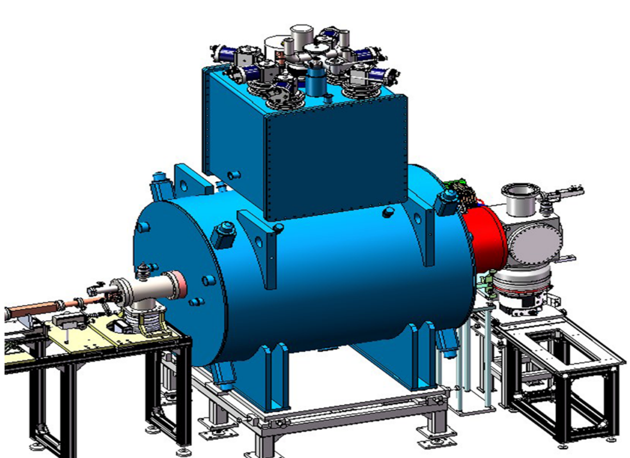

FIG. 12. Schematic view of 45 GHz FECR.

B. Design of FECR Nb_3Sn magnet

A typical magnet of the superconducting ECR ion source is composed of 3 solenoid coils providing the mirror magnetic field for axial confinement and one sextupole for radial confinement. The first important decision for the FECR Nb_3Sn magnet should be the magnet structure. There are three options of the magnet structure available for the FECR magnet. The first one is the conventional magnet structure where the sextupole is located inside of the three solenoid coils, and this coil configuration has been utilized by most of the superconducting ECR ion sources, such as LNS-SERSE,[6] LBNL-VENUS,[8] RIKEN-SCECRIS,[12] and MSU-SuSI.[13] The second one is the SECRAL-type magnet structure where the three solenoid coils are located inside the sextupole bore.[11] The third one is a new magnet structure with a close-loop Ioffe-bar sextupole that the sextupole coil ends are efficiently utilized to provide axial mirror fields, which was proposed by Xie.[25,26] The ECR plasma is independent of any differences in the magnet structure if the minimum-B magnetic field distribution is properly designed and realized. If the designed magnetic fields can be reached, the most important considerations for the choice of the magnet structure are the smaller coil-current density,

TABLE II. Main design parameters of 45 GHz FECR.

Microwave	45 GHz at 20 kW
Magnet conductor	Nb_3Sn
Axial mirror fields (T)	6.5/1.0/3.0
Mirror length (mm)	500
Sextupole field at the chamber wall (T)	3.8
Maximum field on the conductor (T)	11.8
Warm-bore ID (mm)	Ø165
Plasma chamber ID (mm)	Ø150
Magnet length (mm)	1420
Extraction voltage (kV)	50
Typical beam	1.0 emA $^{238}U^{35+}$

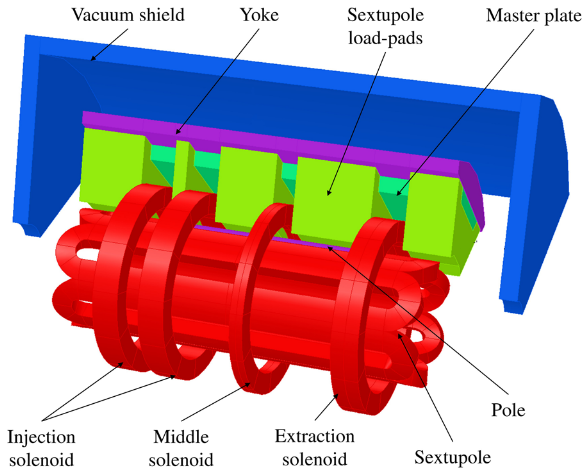

FIG. 13. FECR Nb_3Sn magnet structure and components.

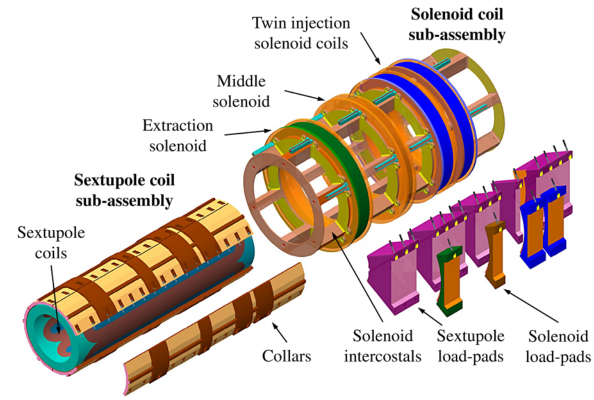

FIG. 15. Main subassemblies and components of the final coil pack.

less stress and strain on the conductor, higher operation safety margin, better stability and reliability, engineering feasibility of manufacturing with reasonable cost, and project schedule as well. The third option of the close-up sextupole magnet structure has the obvious advantage of high field efficiency, but it needs strong effort of prototyping and also the sextupole coil winding is quite engineering-complicated and risky for high field operation. The second option of the SECRAL-type magnet structure has to be energized to a loading factor of more than 90% to achieve 45 GHz magnetic fields, and the maximum stress on the conductor is quite high.[27] After detailed calculation and analysis, finally the first option of the conventional structure is the decision made for a FECR Nb_3Sn magnet.

The second important decision for the FECR Nb_3Sn magnet is the magnet coil winding which should be wound with single Nb_3Sn wire or cable. FECR will be used as an external ion source of the HIAF linac injector and will be installed at a 100 kV high voltage platform to meet the injection beam energy requirement. The Nb_3Sn cable winding technology has been developed for an accelerator magnet, such as the high field large-aperture quadrupole of LHC (Large Hadron Collider) luminosity upgrade.[28] The cable-winding magnet can be operated with a better reliability and easier quench protection system, but is not feasible for cold-mass cooling with compact cryo-coolers, and is quite challenging for the cryogenic system on a high voltage platform. The wire-winding magnet operating at lower coil current can be cooled down by cryo-coolers with HTS (high temperature superconductivity) current leads. The main challenge for the FECR Nb_3Sn wire-winding magnet is the sextupole coil winding and quench protection. The final decision is that all the Nb_3Sn coils of FECR magnet will be wound with single wire.

Figure 13 shows the design of the FECR Nb_3Sn magnet structure and key components. The FECR magnet was designed by collaboration with LBNL-ATAP.[29,30] The conventional magnet structure with sextupole-inside-solenoids is utilized. The axial mirror magnetic field is produced by four solenoids. The injection solenoid is split into two sub-coils with an axial gap in order to reduce the longitudinal span between sextupole pads. The magnet support structure is based on an aluminum shell surrounding the coils and iron yoke, pre-tensioned using water-pressurized bladders and interference keys.[29] The aluminum shell supports the sextupole through longitudinally segmented loading pads placed in between solenoids, and a thin continuous collar placed above the coil. The solenoids are encased in a stainless steel form and radially supported by a tensioned aluminum wire, with the aluminum shell providing additional support and alignment through a second set of loading pads interleaved with the first set.[29] Axial support is provided to both sextupole and solenoid subassemblies by aluminum rods and end plates. The designed magnet mechanical-structure and main subassemblies are shown in Figs. 14 and 15. The detailed design of the magnet mechanical structure can be found in Ref. 29.

The sextupole is the most challenging part in manufacturing and assembling. Sextupole coils are wound around iron

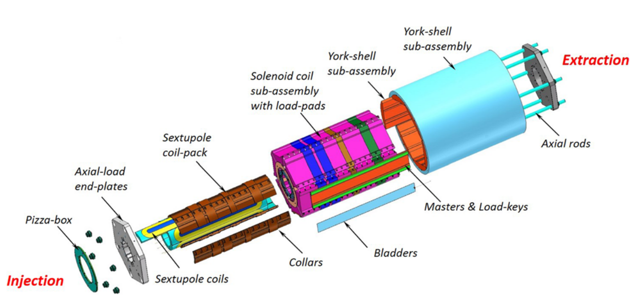

FIG. 14. Exploded view of the FECR magnet structure.

TABLE III. Main parameters of the FECR magnet coils.

Parameters	Inj.	Mid.	Extr.	Sext.
Nominal current (A)	692	380	626	654
Peak field on the conductor (T)	11.8	5.0	9.7	11.3
Inner diameter (mm)	336	336	336	200
Outer diameter (mm)	430	430	430	276
Magnet coil length (mm)	2×60	30	60	587.4
Conductor packing factor	0.7	0.7	0.7	0.65
Loading factor at 4.2 K (%)	78.2	36.5	67.3	75.9

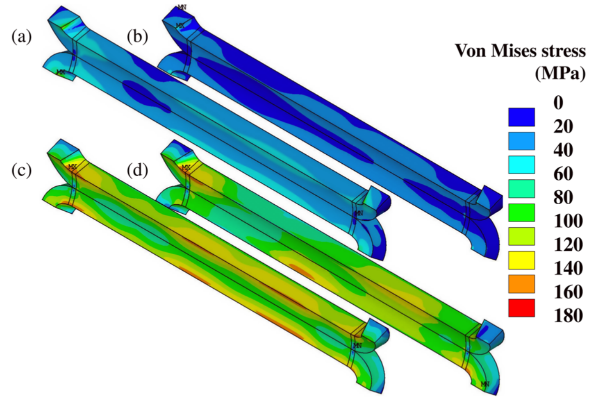

FIG. 16. Von Mises stress in the sextupole during (a) the bladder operation, (b) the room temperature pre-load, (c) cool-down, and (d) excitation.

poles with titanium tips. The conductor at the coil ends is protected by aluminum-bronze end-shoes, and the whole coil is impregnated with an epoxy resin. The arrangement of sextupole coils is surrounded by six full-length stainless steel collars that are bolted together. These collars have optimized cross section that improves their rigidity and allows for more even distribution of the pre-load force transferred from the cylinder by spaced loading pads.[29] All coils of the magnet system are wound with the same Nb_3Sn round single wire. The Nb_3Sn wire diameter is 1.3 mm with additional insulation thickness 0.065 mm, and the critical current density is 2.4 kA/mm^2 at temperature 4.2 K and field 12 T. The parameters of the coil system are summarized in Table III.

It is critical to reduce the maximum stress and strain on the coils during optimized designing of the magnet mechanical structure because Nb_3Sn is a brittle material. The magnet mechanical analysis was performed using the ANSYS software in order to validate and optimize the conceptual design, define the target pre-load level, and evaluate the coil and the structure stress during the magnet assembly, cool-down, and operation.[29] The results of the 2D analysis shows that the proposed concept of the magnet support structure is capable of sufficiently preloading the sextupole coil. During the bladder operation and when keys are inserted at the room temperature, the maximum stress in the coil is approximately 75 MPa and 55 MPa, respectively.[29] After the cool-down, the model shows a maximum stress of approximately 143 MPa in the inner radius pole corner areas.[29] Due to the contribution of the solenoid coil fringe field in the magnet section between two solenoid coils, the stress distribution during the excitation is unsymmetrical and the peak stress of 129 MPa is located close to one of the poles in the high field zone. Figure 16 shows the distribution of Von Mises stress in the sextupole coil.[29] While the calculated stress during bladder operation with all six bladders is approximately 116 MPa, the experience shows that when using one or two bladders at the time the stress value drops to a similar value as with load keys inserted, which is 67 MPa.[29] The stresses after cool-down and with magnetic forces are below 155 MPa, and the peak is located in the coil ends. The radial pre-load is applied to solenoid coils using a 30 mm thick layer of the pre-tensioned aluminum strip and stainless steel pads assembled around the banding in order to couple the solenoid system with the support structure. The maximum stress in solenoid coils after cool-down is 100 MPa and 126 MPa when magnetic forces are applied.[29] The maximum stress 155 MPa in the sextupole coils and the maximum stress 126 MPa in the solenoid coils indicate a more conservative safety-margin for the magnet operation, while the engineering experience shows that the peak stress in Nb_3Sn coils should be within 200 MPa.[28]

The FECR magnet will be the first Nb_3Sn magnet dedicated to the 4th generation ECR ion source. The relevant key technologies need to be prototyped which are being conducted at IMP and XSMT company in Xi'an, China, including coil fabrication, quench protection system, system assembly, and so on. Up to now, sextupole coil fabrication with wire, quench protection,[31] and precise assembly are the most challenging issues to be addressed. A prototype of the FECR magnet consisting of two solenoids and 1/2-length sextupole will be first fabricated and tested in order to verify the designed mechanical structure and accumulate some engineering experiences. Figure 17 shows the structure of the FECR magnet prototype to be built. Nominally, the FECR magnet will be ready by the end of 2019.

C. 45 GHz/20 kW microwave power coupling and double-frequency heating at FECR

20 kW of 45 GHz microwave power is produced by a gyrotron system which was manufactured by GyCOM.[32] The gyrotron operating at fundamental harmonic of electron cyclotron resonance is installed in a 4 T cryomagnet in a LHe-free cryogenic system. By using a water-cooled calorimetric dummy load, the gyrotron system was tested successfully to

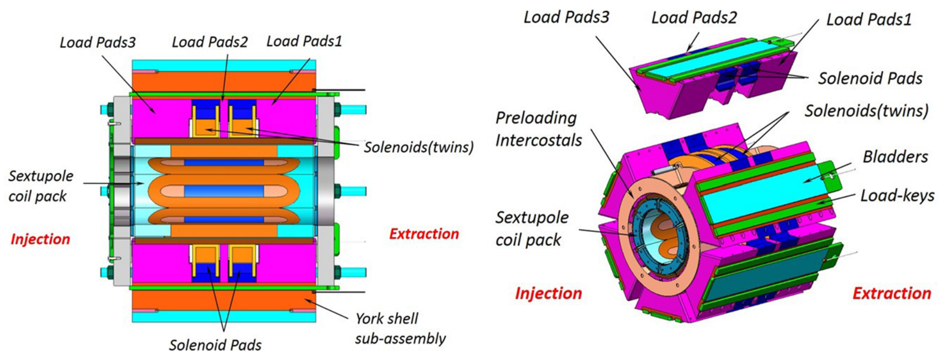

FIG. 17. Structure of the FECR magnet prototype.

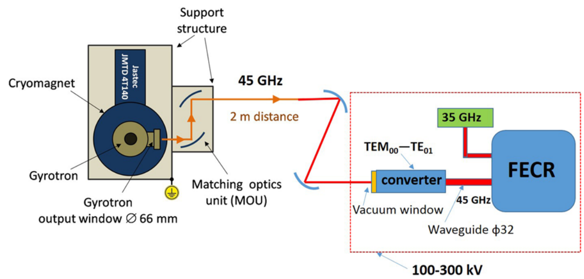

FIG. 18. Schematic view of the 45 GHz microwave gyrotron system and coupling to the FECR ion source.

output 20 kW CW power through an Ø66 mm boron nitride ceramic window with quite good long-term stability. The microwave transmission between the gyrotron system and the FECR ion source is realized through the quasi-optical scheme because FECR is located at a 100-300 kV high voltage platform, as shown in Fig. 18. 45 GHz microwave from the gyrotron system with mode TEM_{00} is converted into mode TE_{01} through a convertor and is coupled into the FECR ion source through a circular waveguide with an inner diameter of Ø32 mm. The gyrotron and its coupling system were tested successfully with SECRAL-II with power up to 5 kW to verify the technical design of the whole system.[24] The 45 GHz gyrotron system with power 20 kW now is ready for an FECR source.

FECR will be operated at double-frequency heating at 45 GHz plus 35 GHz microwaves. The auxiliary microwave frequency was preliminarily chosen as 35 GHz in terms of SECRAL high power operation with 24 GHz plus 18 GHz double-frequency heating. The 35 GHz auxiliary microwave power can be produced by a gyrotron system with maximum output power 3.0 kW. The 35 GHz microwave power will be coupled into FECR through an oversized circular waveguide. However, the preliminary test results with 28 GHz + 45 GHz + 18 GHz at SECRAL-II might indicate that the higher frequency of the auxiliary heating microwave than the main heating frequency would be better for the production of higher charge state ion beams. Further beam tests with 28 GHz + 45 GHz + 18 GHz multiply frequency heating are going on, which may change the decision of 35 GHz microwave frequency as an auxiliary microwave for FECR double-frequency heating.

IV. CONCLUSION

The superconducting ECR source with higher magnetic fields and higher microwave frequency is the most straightforward path to achieve high beam intensity and high charge state. Intensive research studies and developments on high performance superconducting ECR ion sources SECRAL and SECRAL-II operating at 24-28 GHz have been conducted at IMP in order to meet requirements of the existing accelerator facility HIRFL and the future facility HIAF. A number of new record beam intensities, such as 1.4 emA $^{40}Ar^{12+}$, 620 eμA $^{40}Ar^{16+}$, 15 eμA $^{40}Ar^{18+}$, 146 eμA $^{86}Kr^{28+}$, 0.5 eμA $^{86}Kr^{33+}$, 1.1 emA $^{129}Xe^{26+}$, 365 eμA $^{129}Xe^{30+}$, 53 eμA $^{129}Xe^{38+}$, and so on, have been produced by SECRAL and SECRAL-II at high power 6-9 kW of 24-28 GHz operation and multi-frequency heating. Recent beam test results with SECRAL and SECRAL-II have further demonstrated that the production of more intense highly charged heavy ion beams needs higher microwave power and higher frequency. A 45 GHz superconducting ECR ion source FECR is being built at IMP. The optimized design of the FECR Nb_3Sn superconducting magnet and the detailed analysis of the shell-preloading-based mechanical structure illustrate that it is feasible for a 45 GHz FECR source to realize the 6.5 T axial mirror field and 3.5 T sextupole field on the chamber inner wall. As a result of performed optimization, the maximum magnetic field on the sextupole coils is 11.8 T, the maximum field on the solenoid coils is 11.3 T, the maximum stress is 155 MPa in the sextupole coils, and the maximum stress is 126 MPa in the solenoid coils. However, it is actually very challenging for manufacturing such a high field Nb_3Sn magnet, a prototype magnet of FECR is being built to verify the magnet mechanical design. 20 kW at the 45 GHz microwave gyrotron system is ready for the FECR ion source and was first tested with SECRAL-II to validate 45 GHz microwave coupling. The 45 GHz FECR ion source is expected to start beam commissioning by the end of 2019. The development of high performance superconducting ECR ion sources at IMP has demonstrated a technical path for highly charged ion beam production from 24 to 28 GHz SECRAL to 45 GHz FECR.

ACKNOWLEDGMENTS

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